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13. ABSTRACT ***(Maximum 200 Words)***

The goal of this research is to develop stereoscopic techniques for mammographic imaging and to investigate the feasibility of using stereomammography to improve the sensitivity of mammography for breast cancer detection, especially in dense breasts.

During this year, we conducted further studies to investigate the effects of imaging techniques on depth perception and depth measurement in stereomammography. A GE Senographe 2000D full field digital mammography system was used for stereoscopic imaging. We developed a stereoscopic imaging technique in which the phantom was shifted instead of the focal spot for acquisition of the left-eye and right-eye images. In a preliminary observer study, we found that larger stereo angles and zooming facilitate depth measurement with a virtual cursor.

In a separate observer experiment, we evaluated the effects of magnification, contact, and zooming on depth discrimination. We found that the accuracy of depth discrimination increased with increasing fibril depth separation and with increasing x-ray exposure. Zooming the contact stereo images by 2X did not improve the accuracy. Depth discrimination was superior with stereo images acquired using geometric magnification in comparison with images acquired using a contact technique. These studies indicate that stereoscopic imaging may improve the perception of image details and depth separation, and thus may be useful for differentiating overlapping tissues from masses and identifying 3D spatial distribution of microcalcifications in mammography.

Based on the information from these observer studies, it will be possible to design effective imaging techniques for stereomammography. The improvement in perception of the details of mammographic features and the additional size and depth information are expected to improve diagnostic accuracy of mammographic abnormalities.

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(3) Table of Contents

(4) Introduction

The goal of this project is to develop a digital stereoscopic imaging technique for mammography. We hypothesize that stereoscopic imaging can be a practical technique with current detector and display technology and will improve the detection and analysis of breast lesions, especially for dense breasts. The improvement results from the facts that: (1) digital imaging systems generally can provide better contrast sensitivity for imaging dense tissues, (2) the overlying dense tissue will be separated from the lesion in the stereoscopic views thereby increasing the conspicuity of the lesion, and (3) the ability to analyze the 3-dimensional distributions and shapes of lesions such as calcifications and masses within the breast can potentially improve the accuracy of mammographic image interpretation by radiologists and reduce unnecessary biopsies.

To accomplish this goal, we first performed phantom studies to develop an optimal imaging technique for the acquisition of the stereoscopic images. This included the determination of the stereoscopic angle, the magnification factor, and the dose requirements in comparison with those for a single-image technique. To view the digital stereoscopic images, we developed a stereoscopic viewing station with a high-resolution graphics board and monitor. We also developed and implemented software for panning and roaming the displayed image. A stereoscopic viewer with an LCD shutter is used to separate the left eye and right eye images. Any one image of the stereoscopic pair can also be read independently as in a conventional single-image reading condition.

It is expected that this research will result in a practical digital stereoscopic imaging technique, which can improve the sensitivity of mammography for breast cancer detection, especially in dense breasts.

(5) Body

In the third year (4/20/00-4/19/01) of this grant, we have performed the following studies:

(A) Development of Stereoscopic Image Acquisition Technique

In our original grant application, we proposed to use a 5-cm X 5-cm field of view fiber optics coupled CCD camera in a Fischer Mammotest stereotaxic biopsy system for the acquisition of stereo phantom and specimen images. We also proposed to use a high-resolution Computed Radiography (CR) plate to acquire full field direct digital phantom images. In the summer of 2000, our department purchased the first commercially available full field digital mammography (FFDM) system by General Electric Medical System (a GE model Senographe 2000D system). The system has a flat panel CsI-amorphous Si active matrix array detector with a pixel size of 100 μm X 100 μm and a matrix size of about 1900 X 2300 pixels. The system is being used in the breast imaging division of the University of Michigan Medical Center routinely for patient mammograms. It is state-of-the-art and produces images that have image quality superior to that of the full-field digital images we could obtain with our department's CR plate system. We therefore decided to develop our stereoscopic imaging technique using this clinical FFDM system. These studies will replace the proposed studies using the small field CCD digital camera and the CR plates.

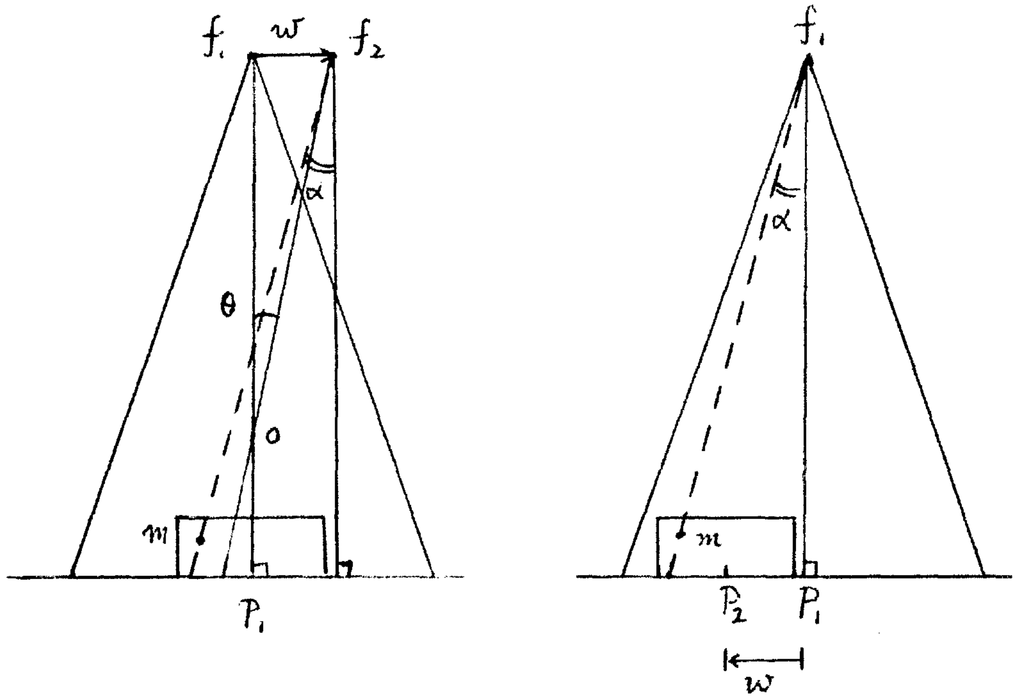
Principle

The FFDM system is designed for conventional projection imaging. In its current clinical mode, the system only allows x-ray exposures when the x-ray tube is oriented perpendicular to the detector surface. It does not permit the acquisition of images at off normal angles (e.g. $\pm 5^o$), which is required in stereoscopic imaging. We therefore could not use the common (tube-shift) method for acquisition of stereoscopic images with the FFDM system. To overcome this limitation, we designed an alternative phantom-shift stereoscopic imaging method, as illustrated in Fig. 1.

Figure 1(a) shows the geometric relationship of the focal spot, the object being imaged, and the x-ray detector. The central position of the focal spot is f_1, and that of the phantom is P_1. To acquire one of the images in a stereoscopic pair, the focal spot is shifted to the right, f_2. The linear distance between f_1 and f_2 is w. As shown in Figure 1(b), if the phantom is shifted by the same distance, w, as the focal spot to position P_2, in a direction parallel to the focal spot shift but in the opposite direction, the relative positions of the focal spot and the phantom are the same as those seen in Fig. 1(a). For example, an object, m, in the phantom will be projected by a primary x-ray at an angle α from the central ray in both cases. Therefore, the image obtained using the tube-shift imaging technique in Fig. 1(a) will be indistinguishable from the image obtained using the phantom-shift imaging technique of Fig. 1(b). The shift distance, w, can be calculated from the stereo angle, θ, by simple geometry:

$$w = d \tan \theta,$$

where d is the distance from the focal spot, f_1, to the fulcrum of rotation, o, of the x-ray system.

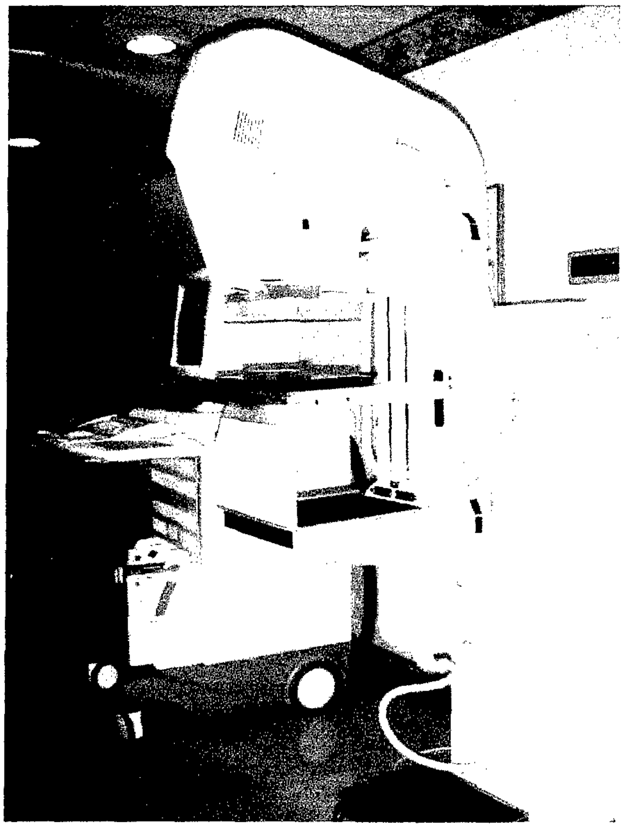


(a) (b)

Fig. 1. (a) Commonly used method for acquisition of stereoscopic image pairs. The x-ray focal spot is shifted to the right (f_2).and the left (not shown) from the central position (f_1).
(b) Our method of acquiring stereoscopic image pairs. The phantom is shifted to the position (P_2) to acquire an image corresponding to the focal spot position f_2 while the focal spot remains at position f_1.

Phantom Shift Device

To facilitate the parallel shifting of the phantom between the left and right-eye positions relative to the central ray of the x-ray beam, we designed and built a phantom shift device, as shown Fig. 2. The device consists of a stationary Lexan platform that fits on the detector cover plate or on the magnification stand. A sliding plate that fits between two parallel guides on the platform is used for moving the phantom in a direction parallel to the chest wall edge of the mammography system. This is also the direction that the focal spot would move if it were used for stereoscopic imaging. A lead marker is fixed on the sliding plate within the field of view and is used for alignment of the stereoscopic image pair before display and viewing. The central location of the sliding plate is marked on the plate. The left, right, and central positions for acquiring a left, a right, and a 0° image are marked on the chest wall guide as positions #1, #2, and #3, respectively, as can be seen in Fig. 2. The positions #1 and #2 are at distances of $\pm w$ from the central position. For our x-ray system, d=46 cm, therefore, a $\pm 3^{\circ}$ stereo angle corresponds to shifts of ± 2.41 cm, which are the marked locations shown in this picture. To acquire a stereo image pair of a phantom, we place the phantom on the sliding plate and fix its position. The sliding plate is aligned at position #1, and an exposure is made. The plate is then shifted to position #2, and an exposure with exactly the same kVp and mAs as that used for position #1 is made. The digital image pair is then transferred to our workstation for image processing and display.



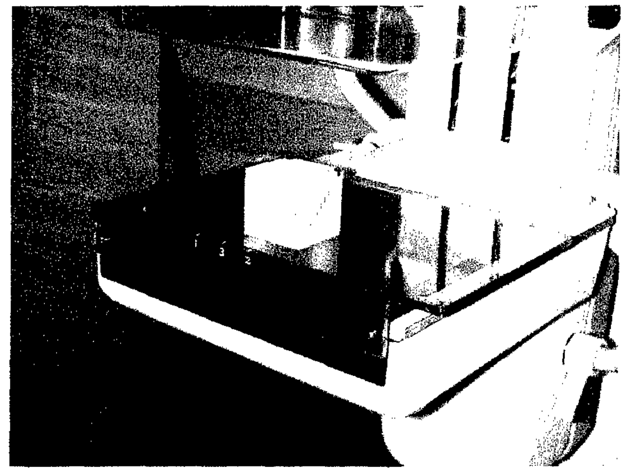


Fig. 2(a). The GE full field digital mammography system. The stereo imaging phantom shift device is shown mounted on the magnification platform, in a configuration for acquiring stereo magnification images

Fig. 2(b). The stereo imaging phantom shift device is shown mounted on the detector in a contact imaging configuration. A stepwedge calibration phantom is placed on the sliding plate to demonstrate phantom positioning. The sliding plate in this photo is aligned at the position for acquiring a right-eye image.

(B) Design and Built new Stereoscopic Breast Phantoms

We designed two stereoscopic breast phantoms and had CIRS, Inc. build prototypes of these phantoms. The first one is a rigid breast shape phantom in which 10 groups of simulated microcalcifications and 8 spiculated masses are embedded at different depths. The depths of the center of each group of microcalcifications and masses are provided by the manufacturer. In Fig. 3(a), we show a photograph of the phantom on top of which a piece of blue "SMUD" (a PLAYDO-like substance manufactured by Mattel, Inc.) was molded into an irregular shape to simulate dense tissue. The right-eye image in a stereo pair of the phantom with the "dense tissue" is shown in Fig. 3(b). The SMUD produces an under-penetrated area in the x-ray image similar to that in a very dense breast. In Fig. 4, we show a stereo image pair without the "dense tissue" to illustrate the test objects in the phantom.

The second phantom is a compressible breast shape phantom with simulated clustered microcalcifications and masses suspended in a tissue-equivalent gel. A photograph of the phantom and the right-eye image in a stereo pair of the phantom are shown in Figs. 5(a) and 5(b), respectively.

Fig. 3(a). The stereoscopic breast phantom with a piece of blue simulated dense tissue. The stereo imaging phantom shift device is mounted on the detector platform in the contact-imaging configuration.

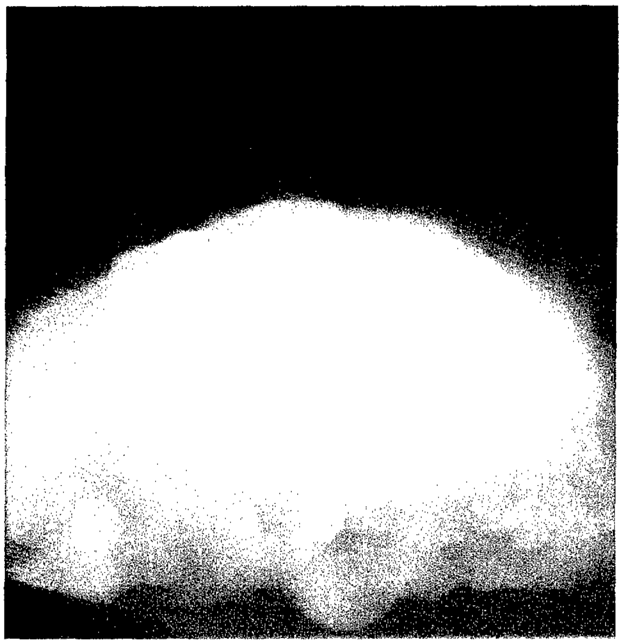


Fig. 3(b). The right-eye image of the breast phantom, demonstrating the underpenetrated area due to the "dense tissue." A few of the simulated masses near the periphery of the dense tissue can be seen. The left-eye image is similar except for the stereo shift and is not shown here.

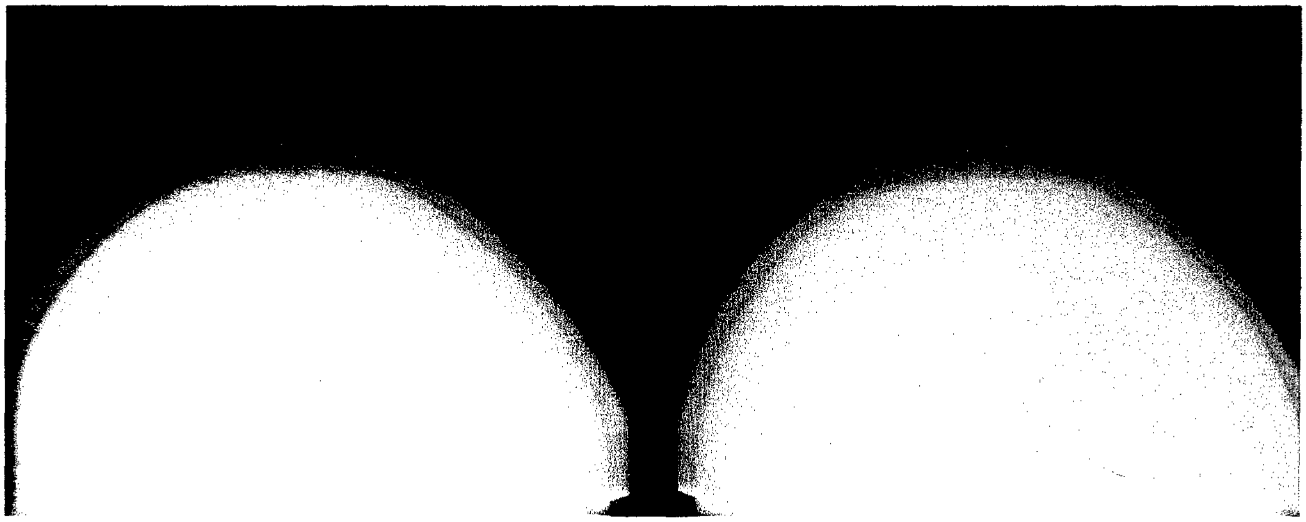
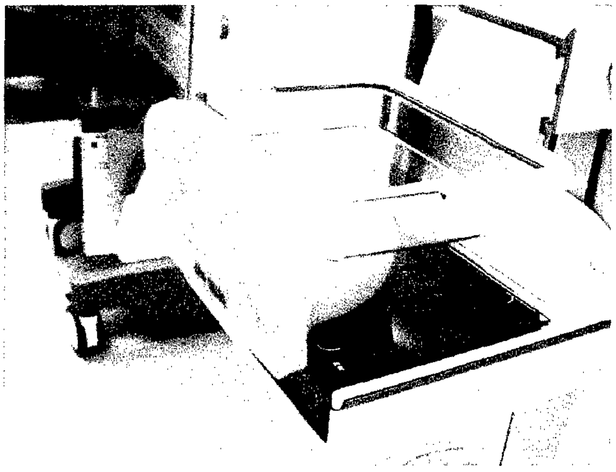


Fig. 4. The same stereoscopic breast phantom imaged without the simulated dense tissue. The 8 simulated masses are seen, but the spiculations and the microcalcification clusters are not visible in this minified reproduced image: Both the left-eye image and the right-eye image are shown here to demonstrate the stereo-shift of the test objects in the image pair. In particular, notice that the bottom right objects are better separated in the right eye image than in the left eye image.



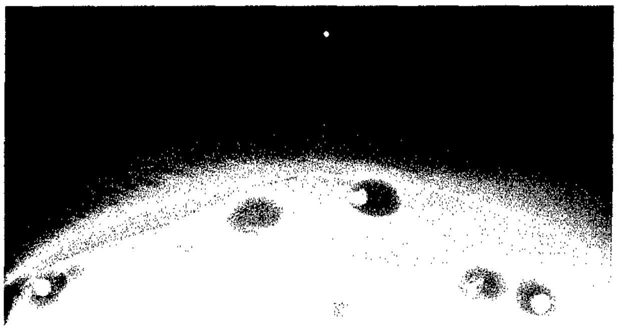


Fig. 5(a). The compressible breast phantom shown in the contact-imaging configuration.

Fig. 5(b). The right-eye image of the compressible breast phantom, demonstrating the "dense tissue" and the simulated lesions of microcalcifications or masses. The left-eye image is similar except for the stereo shift and is not shown here.

(C) Phantom Evaluation of Full Field Steremammography

We performed phantom studies using the stereoscopic breast phantoms described above. Stereoscopic images of the phantoms were acquired with the FFDM system at various exposure levels. The images were aligned to be a stereoscopic pair that can be displayed on our viewing station. That viewing station was described in detail in our annual report last year. Briefly, the stereo viewing station consists of a high-resolution Barco monitor driven by a Metheus stereo graphics board installed in a SUN Microsystem workstation. The Metheus board has a matrix of 1400X1400 pixels and 12-bit gray level resolution. The displayed images are viewed with NuVision LCD stereo glasses. We developed a software package that includes functions such as display of a stereo image pair, brightness and contrast enhancement, zooming and panning, and custom design and display of stereo virtual cursors for depth measurement. The display workstation has been used for observer studies evaluating the visibility of simulated mammographic objects, and evaluating the accuracy of depth measurements made with virtual cursors.

From our evaluations of the stereoscopic phantom images, we have made several observations. For both the rigid phantom and the compressible breast phantom, stereoscopic imaging allows the differentiation of the depths and the relative spatial relationships of the various test objects in the phantom. This spatial information is not available in a conventional projection image. It is expected that the 3-dimensional (3D) spatial distribution of the microcalcifications will be useful for differentiating malignant and benign clusters such as vascular calcifications or calcifications within the tissue layers. The spicules around the simulated masses were also clearly identified as radiating from the central mass, rather than projections of overlapping structures from different origins. These phantom studies indicate that the 3D information may have a potential to improve the diagnostic accuracy of suspicious breast lesions on mammograms. However, further studies with a large number of patient stereomammograms will be needed to evaluate the effects of stereomammograms on radiologists' ability of characterizing breast lesions. This is out of the scope of this project. Our studies also indicate that the stereo breast phantoms will be useful for evaluating full breast stereoscopic imaging techniques for this project and for future development.

Another observation from our phantom experiments is that, in stereoscopic imaging, the piece of simulated dense tissue placed on top of the phantom is very different from real dense breast tissue mixed with adipose tissue inside the breast. In a projection image like a conventional mammogram, the simulated dense breast image is very similar to real dense breast mammograms. Because there is no depth separation, the image of overlapping dense tissue at different depths is very similar to an image of a phantom with all dense tissue pressed into one solid piece. However, in stereomammography, the dense tissue of a real breast can be seen to separate into thinner layers or strands at different depths and becomes more transparent. The camouflaging effects of the dense tissue are thus greatly reduced by stereoscopic viewing. Subtle structures or lesions obscured by the dense tissue in a projection image may become more visible in stereo images. The stereoscopic phantom image with a solid piece of "dense tissue" on top of the phantom does not show a similar separation effect of the tissue. The dense tissue is viewed as a dense layer in front of the breast image. The camouflaging effects of the dense tissue are therefore almost the same as those in a projection image. These results indicate that a stereo dense breast phantom must be built with the "dense tissue" dispersed randomly into different depths and mixed with the other tissue-equivalent materials and test objects. This will be very challenging because a 3D model with a realistic distribution of dense and adipose tissues has to be designed and new methods may have to be developed to build such a phantom. This information will be useful for researchers who will design stereoscopic breast phantom in the future.

(C) Evaluation of the Effect of Zooming on Depth Measurements in Digital Stereomammograms

We are developing virtual 3-D cursors for measuring depths in digital stereomammograms [Goodsitt 2000]. Our previous studies showed viewing the images at a 2X-zoom factor did not improve the measurement accuracy. Those studies employed 50-micron pixel images created with a Fischer biopsy unit. We performed a similar study with 100-micron pixel images created with a GE Senographe 2000D digital mammography unit. A phantom containing 25 low contrast fibrils at depths ranging from 1 to 11 mm with a minimum fibril spacing of 2-mm was imaged. The fibrils were oriented vertically (perpendicular to the x-ray tube shift direction) for stereo image acquisition. Left and right eye images were generated at stereo shift angles of +/- 2.5° and 5°. Observers viewed these images with stereo glasses in normal and 2X zoomed mode and adjusted the positions of a cross-shaped virtual cursor to best match the perceived location of each fibril. For an experienced observer, the standard errors of the estimates (SEEs) of the least-square fits to the measured vs. true depths (Fig. 6) were 0.59 0.50, 0.31, and 0.19-mm for the 2.5 °, 2.5 ° zoom, 5 °, and 5 ° zoom images, respectively. The corresponding RMS errors were 0.59, 0.94, 0.39, and 0.40-mm. Use of the 5° stereo angle improved depth accuracy (RMS error) by 34%. Although zooming the images did not improve measurement accuracy, the stereo effect was more readily visualized. This was more apparent than in the 50-micron pixel case. Also, the consistencies of measurements as determined by the SEEs were improved with zooming. Studies with additional observers and for alternative depth calibration methods will be conducted.

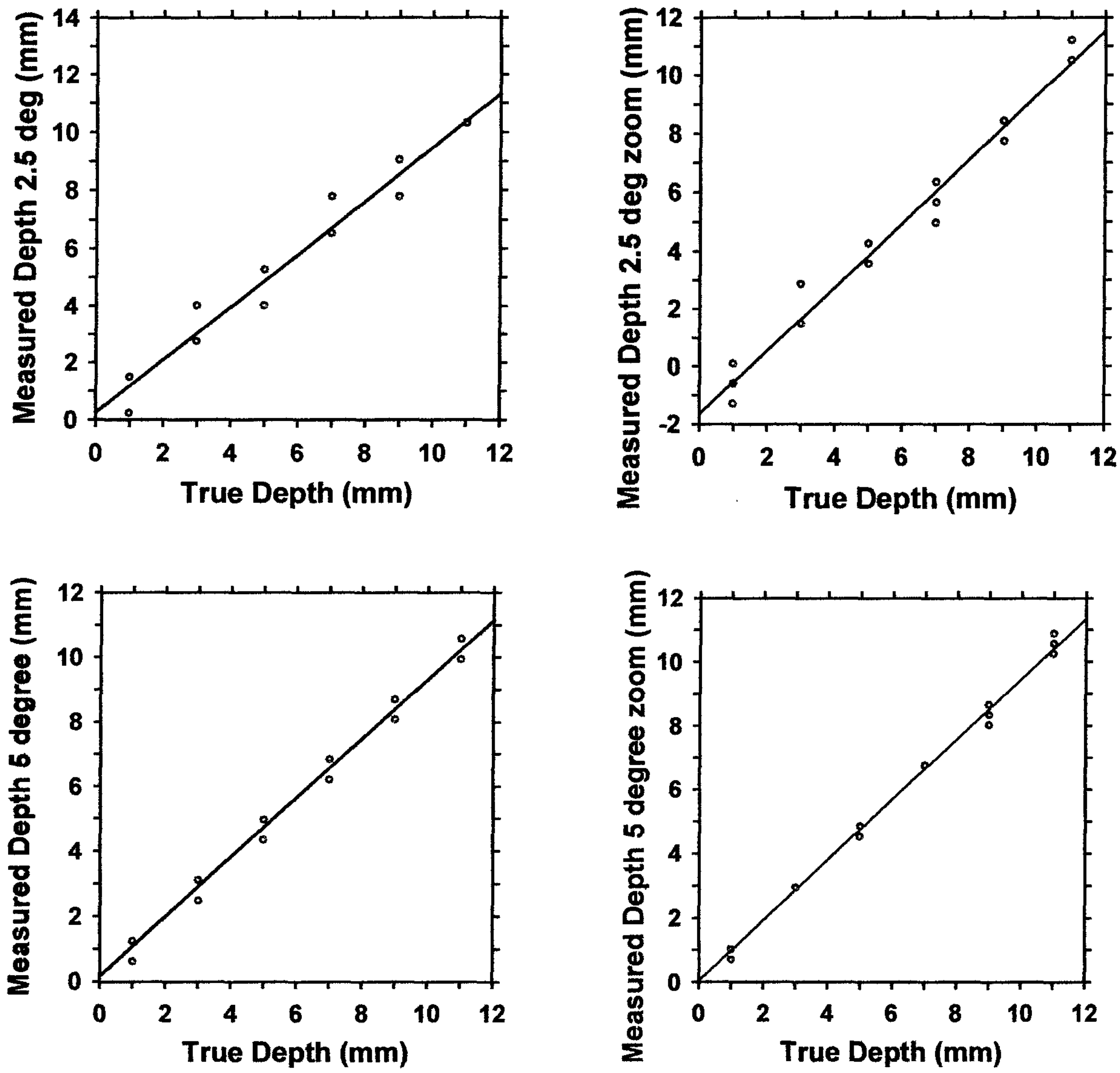


Fig. 6 Linear least-square fits to the measured vs. true depths of the fibrils in the phantom. Results are shown for a very experienced observer when viewing images with stereo angle, display techniques of ±2.5°, normal display (top left), ±2.5°, 2X zoom display (top right), ±5°, normal display (bottom left), and ±5°, 2X zoom display (bottom right).

(D) Effects of Magnification and Zooming on Depth Perception in Digital Stereomammography

We performed an observer study to compare depth perception in contact, zoomed, and magnification stereomammography using phantom images of mammographic test objects. Stereo image pairs were acquired with a GE Senographe 2000D digital mammography system using a technique that shifted the object being imaged instead of the focal spot, as described above. A modular phantom that contained fibrils embedded on six different layers of Lexan, each layer separated by 2 mm, was designed and built. A photographic picture and an x-ray image of the modular phantom are shown in Figs. 7(a) and 7(b). The fibrils were positioned at random locations within a 5×5 matrix on each layer. A total of 25 fibrils were oriented horizontally and 25 vertically. The fibrils were arranged such that a horizontal and a vertical fibril overlapped as a cross in a projection image. Each image contained 25 crossing fibril pairs in the 5×5 matrix. The layers could be randomly ordered to produce different fibril depth separations at different locations of the matrix. The depth separation of every two crossing fibrils ranged from 2 mm to 10 mm in each phantom configuration.

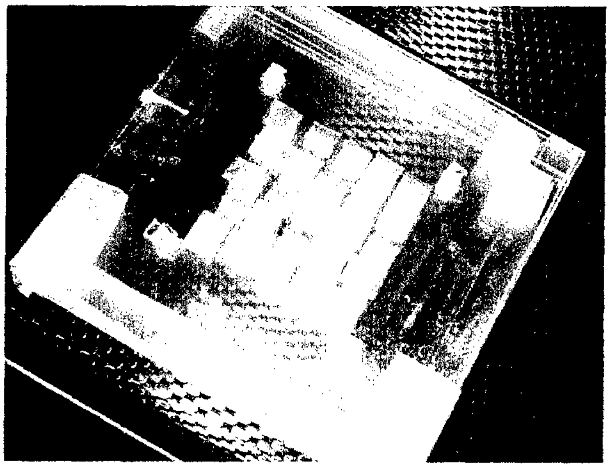


Fig. 7(a). The modular cross fibril phantom with the 5X5 matrix of crossing fibrils visible.

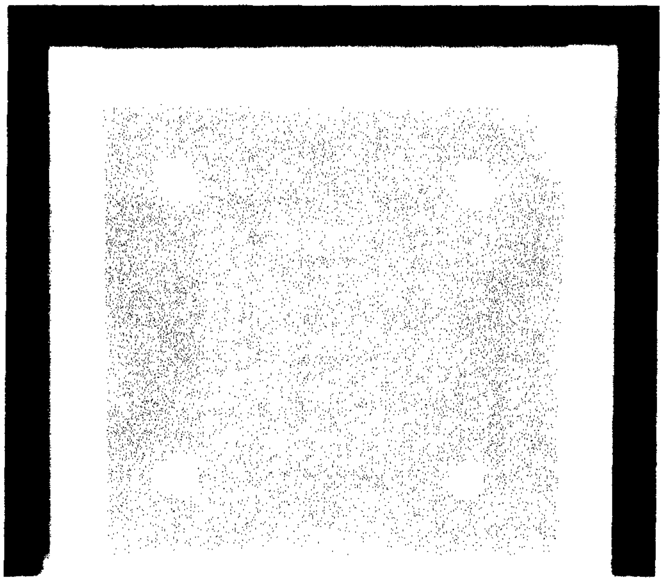
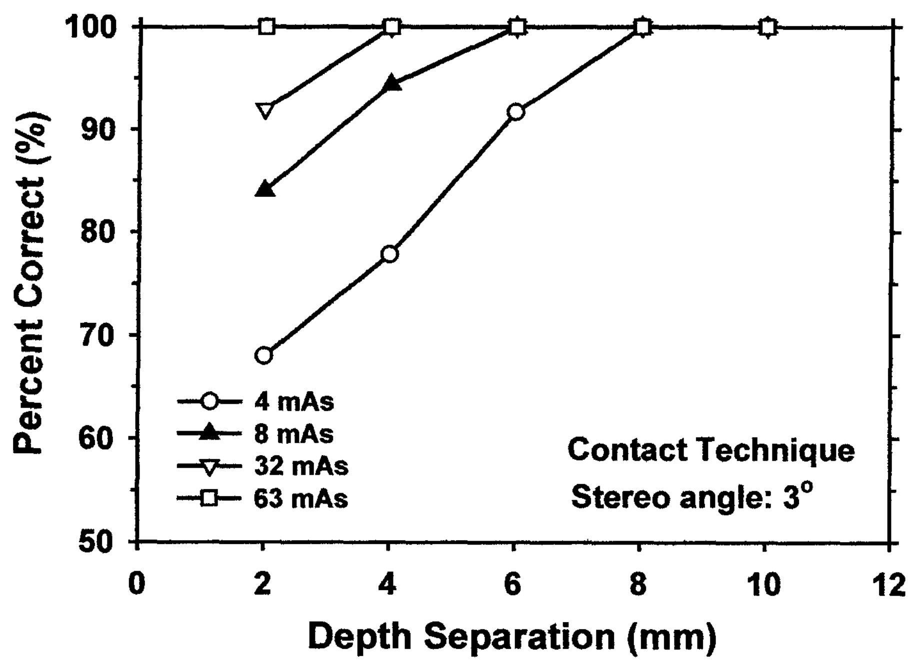


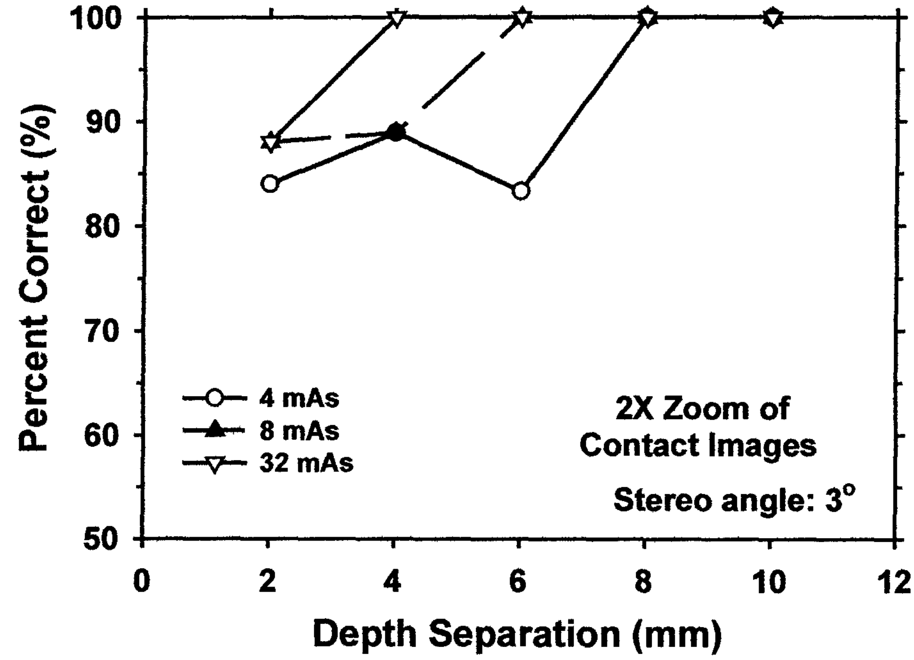
Fig. 7(b). The right-eye image of the fibril phantom. The 5X5 matrix of crossing fibrils can be seen. The four white areas are the spacers that keep the Lexan plates at the desired spacing of 2 mm between adjacent layers. The left-eye image is similar except for the stereo shift and is not shown here.

Three phantom configurations were imaged in this study. Stereoscopic pairs of images were acquired using techniques of $\pm 3^{\circ}$ stereo angle, 30 kVp, Rh/Rh, contact, and 1.8X magnification, with an exposure range of 4 mAs to 63 mAs. Stereoscopic pairs of images were also acquired at a ±6° stereo angle, contact and 1.8X magnification with an exposure of 63 mAs. The images were displayed on the stereo workstation, described above. The brightness and contrast of the images were adjusted to enhance the displayed images. The images acquired with the contact technique were also displayed with 2X zooming for reading. The contact, zoomed, and magnification images were randomly ordered and mixed for each observer. Observers visually judged if the vertical fibril in each pair of crossing fibrils was in front of or behind the horizontal fibril.

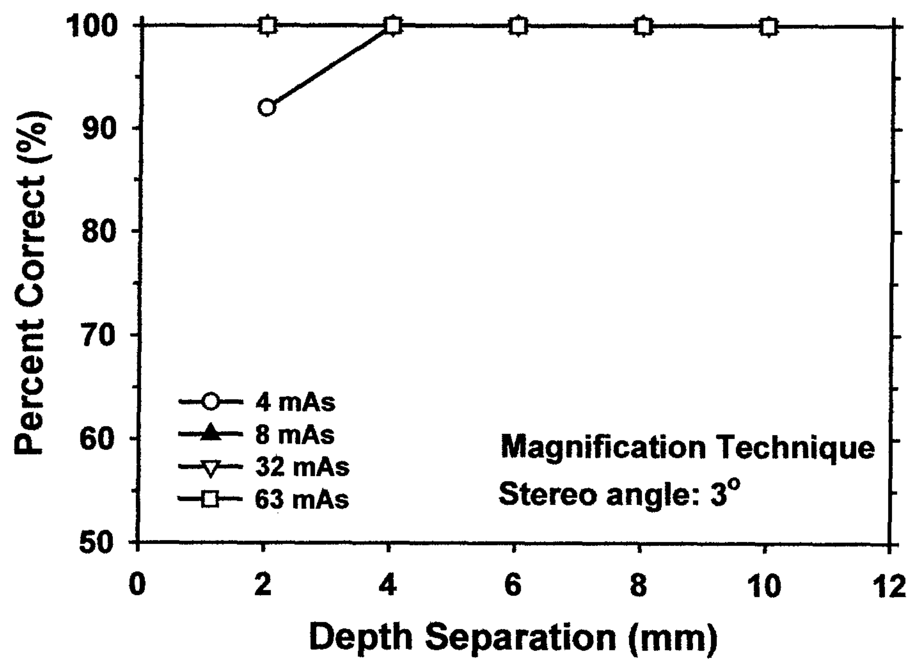
The preliminary results of our study are summarized in Figs. 8(a)-(c). It was found that, for the viewing of fibrils that simulated spiculations or thin fibrous structures in mammographic images, the accuracy of depth discrimination increased with increasing fibril depth separation and with increasing x-ray exposure. Zooming the contact stereo images by 2X did not improve the accuracy substantially. Depth discrimination was superior with stereo images acquired using geometric magnification as opposed to a contact technique. A stereo angle of ±6° resulted in 100% correct detection under both contact and magnification imaging geometry. This study therefore indicates that depth discrimination in stereomammography depends on the imaging technique. Both contact and magnification stereoscopic imaging may improve the perception of image details and depth separation, with greater improvement attained in the magnification mode. Digital stereomammography may be useful for differentiating overlapping tissues from masses in mammography.



(a)



(b)



(c)

Fig. 7(a)-(c). Preliminary results of our observer experiment comparing the effects of contact, zooming, and geometric magnification techniques on stereoscopic depth perception.

(E) Collection of Stereoscopic Images of Biopsied Breast Tissue Specimens

With the GE digital mammography system and our new image acquisition techniques described in (A) above, we continue to collect stereoscopic images of biopsied breast tissue specimens for our planned observer study. We have also performed a pilot observer study by displaying stereoscopic specimen radiographs of breast lesions to radiologists and mammography technologists. The observers were asked to provide subjective opinions on the displayed image quality in comparison with the plain specimen radiographs that they usually read. Their comments indicate that they are very impressed with the 3-D appearances of the stereo images, and they have a strong interest in this new imaging technique. However, because of the small number of observations used in this pilot study, no conclusion can be drawn about whether the observers can perceive more image information in differentiating malignant and benign lesions. We have requested and obtained approval for a one-year no cost time extension for this study. We will continue to collect digital stereoscopic breast specimen images and perform a more extensive observer study in the coming year.

(6) Key Research Accomplishments

- Developed a stereoscopic image acquisition technique and built a phantom shift device for acquiring stereoscopic image pairs with a clinical full field digital mammography system -- (This technique was not proposed in the SOW but is related to Task 3, Task 4, and Task 5)
- Designed and built stereoscopic 3D breast phantoms with embedded test objects for phantom studies with the full field mammography system -- (Task 1 and Task 5)
- Performed observer experiments to study the effects of image zooming on the accuracy of depth measurements in digital stereomammograms using 3D virtual cursors -- (3D virtual cursor and quantitative depth measurement were not in the SOW but are related to Task 3, Task 4, and Task 5)
- Performed observer experiment to study the effects of magnification and zooming on depth perception in digital stereomammography -- (Task 5)
- Continue to collect stereoscopic images of biopsied breast tissue specimens and perform pilot observer study -- (Task 4)

(7) Reportable Outcomes

As a result of the support by the BCRP grant, we have conducted extensive studies in stereomammography and will present results in two conferences.

Journal Articles:

Goodsitt MM, Chan HP, Hadjiiski LM. Stereomammography: Evaluation of depth perception using a virtual 3D cursor. Medical Physics 2000; 27: 1305-1310.

Conference Presentation:

1. Goodsitt MM, Chan HP, Hadjiiski LM. The Effect of 2X Zoom on Virtual Cursor Depth Measurements in Stereomammography. Submitted for presentation at the 43rd Annual Meeting of the American Association of Physicists in Medicine, Salt Lake City, Utah. July 22-26, 2001.

2. Chan HP, Goodsitt MM, Hadjiiski LM, Paramagul C, Bailey J. Digital Stereomammography - Dependence of Depth Perception on Imaging Technique. Submitted for presentation at the 87th Scientific Assembly and Annual Meeting of the Radiological Society of North America, Chicago, IL, November 25-30, 2001.

(8) Conclusions

During this year, we conducted further studies to investigate the effects of imaging techniques on depth perception and depth measurement in stereomammography. A GE Senographe 2000D full field digital mammography system was used for stereoscopic imaging. We developed a stereoscopic imaging technique in which the object (e.g. phantom) was shifted instead of the x-ray tube focal spot for acquisition of the left-eye and right-eye images. In a preliminary observer study, we found that use of a greater stereo angle (e.g. 5 degrees instead of 2.5 degrees) and zooming of the displayed images facilitate depth measurement with a virtual cursor. Accuracy increased with the larger angle. For 2X zooming, although the accuracy of measurement did not change, the standard error of the estimates decreased, indicating the measurements were more consistent.

In a separate observer experiment, we evaluated the effects of magnification, contact, and zooming on depth discrimination. We found that the accuracy of depth discrimination increased with increasing fibril depth separation and with increasing x-ray exposure. Zooming the contact stereo images by 2X did not improve the accuracy. Depth discrimination was superior with stereo images acquired using geometric magnification in comparison to those acquired using a contact technique. Depth discrimination in stereomammography depends on the imaging technique. Stereoscopic imaging may improve the perception of image details and depth separation. This technique may be useful for differentiating overlapping tissues from masses and identifying 3D spatial distribution of microcalcifications in mammography.

Based on the information from these observer studies, it will be possible to design effective imaging techniques for stereomammography. The improvement in perception of the details of mammographic features and the additional size and depth information are expected to improve radiologists' diagnostic accuracy in detecting and characterizing mammographic abnormalities.

(9) References

1. Goodsitt MM, Chan HP, Hadjiiski LM. Stereomammography: Evaluation of depth perception using a virtual 3D cursor. Medical Physics 2000; 27: 1305-1310.

(10) Appendix

Copies of the following publications are enclosed with this report:

Journal Article

Goodsitt MM, Chan HP, Hadjiiski LM. Stereomammography: Evaluation of depth perception using a virtual 3D cursor. Medical Physics 2000; 27: 1305-1310.

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Stereomammography: Evaluation of depth perception using a virtual 3D cursor

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We are evaluating the usefulness of stereomammography in improving breast cancer diagnosis. One area that we are investigating is whether the improved depth perception associated with stereomammography might be significantly enhanced with the use of a virtual 3D cursor. A study was performed to evaluate the accuracy of absolute depth measurements made in stereomammograms with such a cursor. A biopsy unit was used to produce digital stereo images of a phantom containing 50 low contrast fibrils (0.5 mm diam monofilaments) at depths ranging from 1 to 11 mm, with a minimum spacing of 2 mm. Half of the fibrils were oriented perpendicular (vertical) and half parallel (horizontal) to the stereo shift direction. The depth and orientation of each fibril were randomized, and the horizontal and vertical fibrils crossed, simulating overlapping structures in a breast image. Left and right eye images were generated by shifting the x-ray tube from $+2.5°$ to $-2.5°$ relative to the image receptor. Three observers viewed these images on a computer display with stereo glasses and adjusted the position of a cross-shaped virtual cursor to best match the perceived location of each fibril. The x, y, and z positions of the cursor were indicated on the display. The z (depth) coordinate was separately calibrated using known positions of fibrils in the phantom. The observers analyzed images of two configurations of the phantom. Thus, each observer made 50 vertical filament depth measurements and 50 horizontal filament depth measurements. These measurements were compared with the true depths. The correlation coefficients between the measured and true depths of the vertically oriented fibrils for the three observers were 0.99, 0.97, and 0.89 with standard errors of the estimates of 0.39 mm, 0.83 mm, and 1.33 mm, respectively. Corresponding values for the horizontally oriented fibrils were 0.91, 0.28, and 0.08, and 1.87 mm, 4.19 mm, and 3.13 mm. All observers could estimate the absolute depths of vertically oriented objects fairly accurately in digital stereomammograms; however, only one observer was able to accurately estimate the depths of horizontally oriented objects. This may relate to different aptitudes for stereoscopic visualization. The orientations of most objects in actual mammograms are combinations of horizontal and vertical. Further studies are planned to evaluate absolute depth measurements of fibrils oriented at various intermediate angles and of objects of different shapes. The effects of the shape and contrast of the virtual cursor and the stereo shift angle on the accuracy of the depth measurements will also be investigated. [S0094-2405(00)01406-1]

Key words: stereomammography, stereoscopic, virtual cursor, three-dimensional

I. INTRODUCTION

Presently, screening x-ray mammography is the only technique that has a proven capability for detecting early stage clinically occult cancers.[1] Although mammography has a high sensitivity for detecting breast cancers, studies have shown that radiologists do not detect all carcinomas that are visible on retrospective analyses of the mammograms.[2–11] These missed detections are often a result of the very subtle nature of the mammographic findings. One of the major deficiencies of mammography is the inability to discern masses and microcalcifications hidden in dense fibroglandular tissue.[12] It is estimated that about 20% of the breast cancers in dense breasts are not detected by mammography.[9,11] Conventional mammography is a two-dimensional projection image of a three-dimensional structure. As a result, objects along the same x-ray beam path overlap each other. The overlying tissue structures often obscure the visibility of subtle lesions of interest in the mammogram. The camouflaging of the anatomical structures is the main cause of missed diagnoses. Overlapping structures can also project onto the image plane forming shadows that appear to be lesions, resulting in false positive findings. Radiologists examine two or more projections of each breast to improve their ability to detect lesions and to assist them in distinguishing between true lesions and overlapping tissues. However, standard mammographic techniques are not always successful in distinguishing true lesions from overlapping tissues. Digital stereomammography is a method that could potentially solve many of these problems.

Stereomammography is not a new technique. It was first described in 1930.[13] Like other forms of stereoradiography at that time, it involved taking two film images, a left eye image and a right eye image. These were obtained by positioning the x-ray tube at a certain distance to the left and to the right of the central axis. Usually, the total tube shift was 10% of the source-to-image distance.[14] The radiologist would view the images using a cross-eyed technique or a special stereoscopic viewer.[14] Stereoradiography and stereomammography lost favor because of the increased radiation dose, procedure time, and film costs associated with taking two radiographs, and because it generally took more time to read stereoradiographs. According to *Christensen's Physics of Diagnostic Radiology*,[14] another reason for reduced use of stereoradiography was radiologists' disappointment with the technique because they failed to appreciate the fact that stereoradiography did not enable them to accurately judge the distances between objects. Rather, stereoradiography allowed for relative depth perception, whereby one could "accurately rank objects in their order of closeness."[14]

The advent of digital imaging techniques and video image displays has made stereoradiography and stereomammography attractive again. Research has been performed in digital stereoangiography[15–17] and digital stereomammography.[18,19] Furthermore, stereotaxic techniques have been developed for core biopsies of breast lesions. In stereotaxic breast biopsies, much larger stereo angles (+15° to the right and −15° to the left) are employed, compared to the angles used in stereoscopic visualization. These larger angles result in increased parallax ("the apparent displacement of an object when viewed from two different vantage points"[14]) which in turn permits more accurate depth determination. With stereotaxic techniques, the operator identifies the location of the lesion in each image, and a computer calculates the spatial coordinates [x, y, and z (depth)] of the lesion using equations derived from simple geometry.[20] For example the distance of the lesion from a fixed image receptor, z_l, is given by the equation

$$z_l = x_{ls}/(2\tan(15°)),$$

where x_{ls} is the parallax shift of the lesion on the image receptor.[20]

This capacity to measure absolute depths contradicts the relative depth perception limitation of stereoradiography mentioned by Christensen, and in considering this, we conceived the idea of using a virtual (3D) cursor to determine the positions of lesions within a stereoscopic image. The proposed virtual cursor would be calibrated in the x, y, and z directions and would be displayed and moved within the stereoscopic image. To our knowledge, such a cursor has never been developed or used in stereoradiography. We performed a literature search and did find that stereographic cursors or pointers have been developed and tested for other purposes, especially for computer graphics and for the operation of robots in remote environments.[21–24] The application of these cursors to x-ray images as opposed to video or computer graphic images is quite different because x-ray images result from transmission rather than reflection and therefore have a more cloudlike, transparent/translucent quality. Furthermore, additional depth cues due to perspective (closer objects appearing larger than distant objects), occlusion (closer objects obscuring distant objects), shadows (in particular, interactive shadows that move as the objects' positions change), and texture (closer objects having more distinct surface features)[25] are not apparent in radiographs.

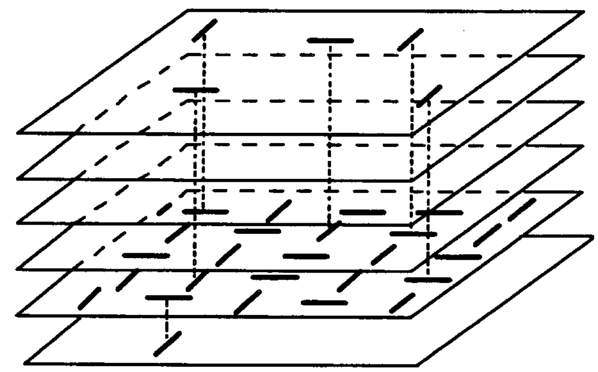

FIG. 1. Diagram of the stereo phantom with simulated fibrils. There are six layers of 1-mm-thick Lexan plates. In the design employed, one of the layers (the second lowest one in this illustration) is superimposed with a 5×5 array of fibrils randomly oriented in two directions. Each of the other five layers has 5 fibrils placed at randomly chosen locations, with the constraint that no more than 2 fibrils will line up in the same location. The two fibrils at the same location are always oriented perpendicular to each other. For clarity, only 5 fibrils in the top layer and 1 fibril in the bottom layer are drawn. The order of the 6 layers was changed to create the two independent phantoms that were analyzed by each viewer.

The purpose of the present paper is to describe a proof-of-concept study that we performed using a virtual cursor in stereomammography images to determine the depths of selected objects.

II. METHODS

A. Phantom

The phantom that was employed to evaluate the depth accuracy of measurements made with the virtual cursor consisted of six 10-cm×10-cm sheets of 1-mm-thick Lexan separated by 1-mm-thick spacers placed at the corners of each sheet. The test objects were 8-mm long, 0.53-mm diam fibrils [nylon monofilaments (e.g., fish line)], which simulated low contrast spiculations in mammograms. The fibrils were positioned within a 4.5-cm×4.5-cm central region of the Lexan sheets. A total of 50 fibrils were taped to the sheets with 25 oriented perpendicular (vertical) and 25 oriented parallel (horizontal) to the stereo shift direction. The depth and orientation of each fibril were randomized, and the horizontal and vertical fibrils crossed simulating overlapping structures in a breast image. The end result was a 5×5 array of crossed (horizontal and vertical) filaments, each of which could be examined for its depth (see Fig. 1). With this arrangement, the minimum depth difference between the fibrils was 2 mm and the maximum was 10 mm. The order of the six Lexan layers could be varied to create many independent phantom configurations for analysis by each reader. In this study, two configurations were randomly chosen.

B. Stereo image acquisition

The phantom was imaged with a Fischer (Denver, CO) MammoVision Stereotaxic unit. According to *Christensen's*

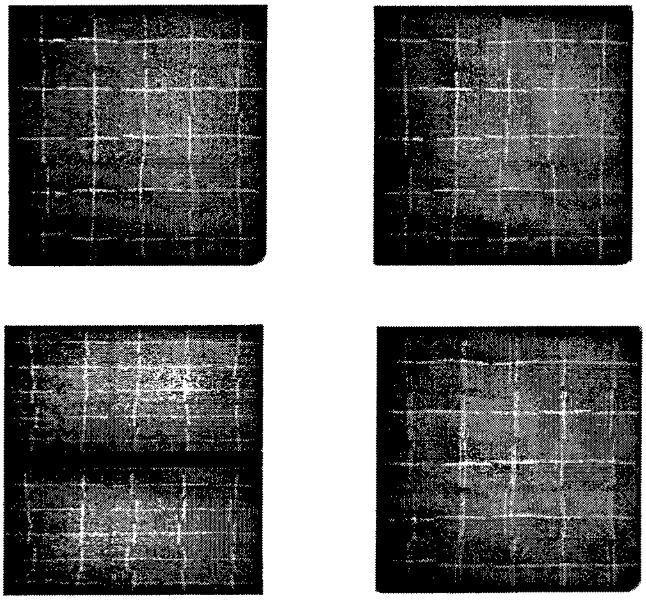

FIG. 2. (Top) Left and right eye images of the phantom shown in Fig. 1. The image pair was obtained with a stereoscopic angle of ±2.5° about the central axis. The fibril pairs with the smallest spacing of 2 mm in this phantom can be identified and the relative depths of the different fibrils can also be clearly distinguished. (Bottom left) Image of the phantom that is stored in the computer frame buffer. This image is synch-doubled by the display processor for stereoscopic viewing. Synch-doubling enables viewing of the left- and right-eye images at twice the nominal refresh rate of the display monitor for reduced flicker. The left-eye image is stored in the frame buffer at the top, and the right-eye image at the bottom. An additional vertical synch pulse is inserted between the two images to produce the two separate images shown at the top of this figure. (Bottom right) Image formed by combining the left- and right-eye images into one. An image similar to this is seen when one views the display without the stereoscopic glasses, and is the one used to calibrate the virtual cursor. The virtual cursor (not shown above) appears as two cursors (a left-eye cursor and a right-eye cursor) when the images are viewed without the stereo glasses, and the horizontal separation between the cursors changes as the cursor depth is adjusted.

Physics of Diagnostic Radiology,[14] early radiologists learned by "trial and error that a tube shift equal to 10% of the target-film distance produced satisfactory results."[14] This tube shift is equal to a total stereo-shift angle of about 6° (e.g., +3° and −3° relative to a line perpendicular to the image receptor.) In general, larger tube shifts produce improved depth perception, but beyond a certain limit, this is achieved at the expense of increased observer fatigue[26] and decreased stereo field of view. The angle scale on the Fischer unit is marked in 5° increments, and our preliminary investigations with the Fischer digital system indicated a stereo shift of +2.5° to −2.5° produced images that appeared to have adequate depth discrimination without producing undue eyestrain. This stereo angle was therefore used for image acquisition in this study. It corresponds with a total stereo shift of about 9% (5.94 cm) for the 68 cm source-to-image distance of the Fischer system. Future studies will be performed to determine the optimal angle for accurate depth perception with acceptable eyestrain. The Fischer unit has a fiber optic-coupled CCD detector that produces 1024×1024 ×12-bit images. The images can be stored in 1024×1024 ×8-bit TIFF format or transmitted to a DICOM server. We

TABLE I. Linear regression results for measured vs true depths in phantom images. (A) Vertically oriented fibrils. (B) Horizontally oriented fibrils.

Reader	Image	Slope	Intercept	r-value	SEE (mm)
(A)					
A	1	1.025	−0.56	0.992	0.39
A	2	1.017	−0.56	0.994	0.38
Average *A*				0.993	0.39
B	1	0.845	−0.65	0.887	1.33
B	2	0.868	−0.61	0.891	1.32
Average *B*				0.889	1.33
C	1	1.087	−1.62	0.963	0.92
C	2	0.955	0.00	0.968	0.74
Average *C*				0.966	0.83
Overall average		0.966	−0.67	0.949	0.85
(B)					
A	1	1.129	−3.04	0.947	1.24
A	2	1.135	−4.66	0.871	2.50
Average *A*				0.909	1.87
B	1	0.003	−5.57	0.004	2.55
B	2	0.176	−7.52	0.154	3.71
Average *B*				0.079	3.13
C	1	0.189	−3.70	0.135	4.54
C	2	0.558	−4.96	0.431	3.83
Average *C*				0.283	4.19
Overall average		0.532	−4.91	0.424	3.06

employed the TIFF formatted images in this study. Since no contrast enhancement was performed on the displayed images in the observer study, it is unlikely that a bit depth greater than 8 bits could have been perceived in the displayed images. Therefore, it is unlikely that compression to 8 bits influenced our results.

C. Stereoscopic viewer and virtual cursor

The images were displayed on a personal computer using a Model SS-03 Stereo Display Processor from Neotek, Inc. (Pittsburgh, PA). We used Neotek's Composer software to format the images and their optional Presenter software to display the images along with a virtual cursor. The Presenter software also generates a display of the x, y, and z-positions of the virtual cursor. The Neotek system produces stereo images via a method termed "synch-doubling." In this method, the left eye image is stored above the right eye image in the video graphics board (see Fig. 2), and an additional vertical synch pulse is inserted between the two images in the video signal coming from the computer. This synch-doubling causes the images to be displayed fully on the monitor at twice the normal refresh rate for reduced flicker (i.e., if the board is run at a 60 Hz refresh rate, the images are displayed at 120 Hz). The graphics board was operated in the 1024 (horizontal)×768 (vertical) resolution mode recommended by Neotek. The Neotek Composer software downsized the 1024×1024 images to fit two images (the left on top of the right) within this resolution. That is, it converted the left and right eye images to each be about

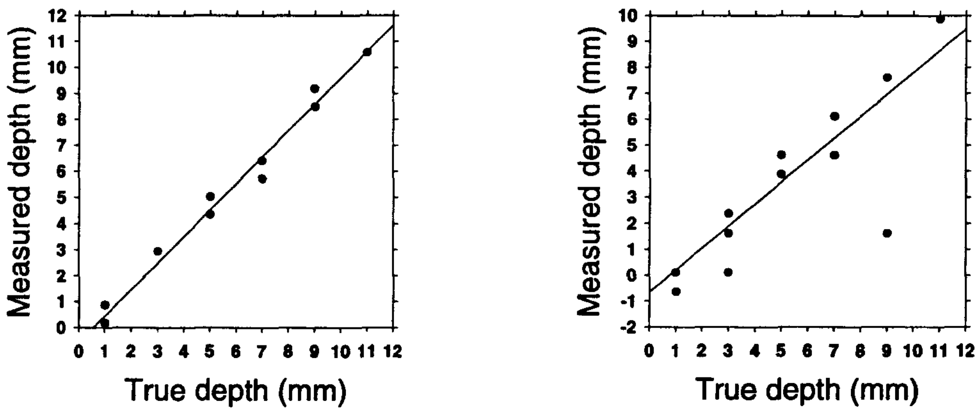

FIG. 3. Plots of the best and worst measured vs true depths of the vertical fibrils for the three readers. The plot with the best accuracy ($r=0.994$, SEE $=0.38$ mm) is shown on the left, and the plot with the worst accuracy ($r=0.887$, SEE$=1.33$ mm) is shown on the right.

1024×340. The loss in vertical resolution was necessitated by the synch-doubling. It had minimal effect in this study since the stereo shift direction corresponding with the horizontal display direction.

D. Observer study

Three observers (two medical physicists and a computer scientist) viewed the images on the computer monitor with a pair of Neotek stereo glasses. These employ LCD shutters that are synchronized with the display to allow viewing of the left image by the left eye and the right image by the right eye. The observers used the up and down arrow keys on the computer keyboard to adjust the position of a cross-shaped virtual cursor to best match the perceived location of each fibril, and noted the z (depth) coordinates on a data sheet.

The z-coordinate was separately calibrated using the known positions of fibrils in the phantom. This was accomplished by viewing the images without the stereo glasses (see Fig. 2) and adjusting the left and right eye cursors to overlay the left and right eye representations of the vertical fibrils in the two images. The z-coordinates of the cursor were linearly fit to the known positions to obtain a calibration line. For the computations, the known depths were taken to be the known distances between the fibrils and the back surface of the phantom.

Each observer analyzed images of two configurations of the phantom. Thus, each observer made 50 vertical filament depth measurements and 50 horizontal filament depth measurements. Linear least-square fits were performed to compare the measurements with the true depths.

III. RESULTS

Table I lists the slopes, intercepts, correlation coefficients (r-values) and standard errors of the estimates (SEE) of the least squares fits to the depth measurements made by the readers in each of the two images that they examined. The results in this table are separated into those for the vertically and horizontally oriented fibrils. Plots of the best and worst results in terms of the standard errors of the estimates are displayed in Figs. 3 and 4. Computed root mean square (RMS) errors for the fibril measurements are listed in Table II.

IV. DISCUSSION

All observers could estimate the absolute depths of the vertically oriented objects fairly accurately in digital stereomammograms; however, only one observer was able to accurately estimate the depths of the horizontally oriented objects. For the vertically oriented fibrils, the overall average r-value was 0.949 and SEE was 0.85 mm. The RMS errors in the depth measurements of the vertically oriented fibrils ranged from 0.6 mm to 1.9 mm with an average value for all three readers of 1.2 mm. These RMS errors indicate that the absolute measurements with the virtual cursor can be accu-

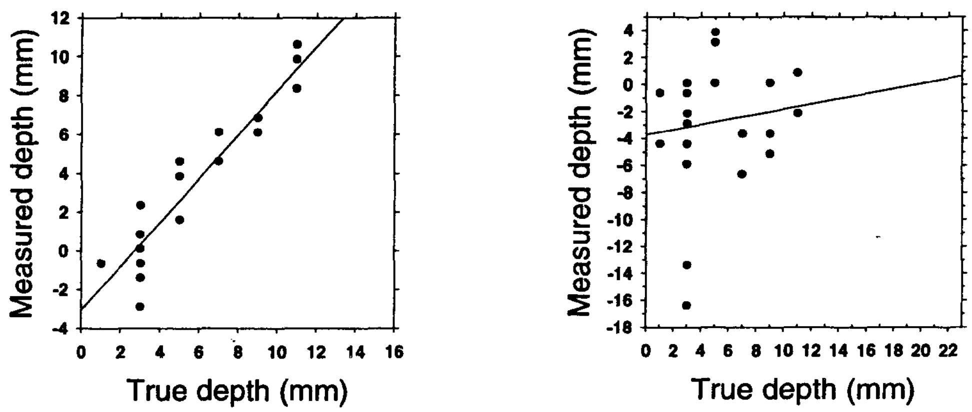

FIG. 4. Plots of the best and worst measured vs true depths of the horizontal fibrils for the three readers. The plot with the best accuracy ($r=0.947$, SEE$=1.24$ mm) is shown on the left, and the plot with the worst accuracy ($r=0.135$, SEE$=4.54$ mm) is shown on the right.

TABLE II. Root mean square (RMS) errors of measured depths of fibrils.[a] (A) Vertically oriented fibrils. (B) Horizontally oriented fibrils.

Reader	Image	RMS error (mm)
(A)		
A	1	0.59
A	2	0.62
B	1	1.91
B	2	1.78
C	1	1.53
C	2	0.75
Overall average		1.20
(B)		
A	1	2.70
A	2	4.76
B	1	11.36
B	2	12.56
C	1	9.30
C	2	8.24
Overall Average		8.15

[a]RMS error $=\sqrt{\Sigma_{i=1}^{25}(\text{true depth}_i-\text{measured depth}_i)^2/25}$.

rate to within 2 mm. This is consistent with relative stereoscopic studies performed by Doi and Duda[26] and Higashida *et al.*[15] and absolute stereoscopic studies performed by Fencil *et al.*[16] Doi and Duda and Higashida *et al.* investigated observers' abilities to distinguish (as opposed to measure) the separation of objects that were superimposed on stepwedge phantoms. In Doi and Duda's study,[26] the objects were 0.2 mm diam aluminum wires. A matrix of "plus" objects were formed by placing horizontally and vertically oriented pieces of wire at the bottom of the stepwedge, with their counterparts located directly above on the step of known thickness (e.g., horizontal wire on step if bottom wire is vertical). The "plus" objects were imaged stereoscopically using a geometric magnification factor of 2 and x-ray focal spot shifts of 1.25%, 2.5%, and 5% of the focus-to-film distance. These investigators found that observers could correctly identify 1 mm separations between two aluminum wires 80% of the time for the 5% tube shift and between 60 and 70% for the other tube shifts. In Hagashida *et al.*'s study,[15] a similar phantom was used. Teflon tube objects filled with contrast media were arranged on the stepwedge to form cross (or "X") shaped objects. They employed a geometric magnification factor of 1.1 and the x-ray focal spot shift for stereoscopic imaging was 6.5% of the focus-to-image intensifier distance. They found that observers could correctly identify 1.6 mm separations between 1 mm diameter tubes containing 25% iodine contrast more than 80% of the time.

Our study and results can be distinguished from those of Doi and Duda[26] and Higashida *et al.*[15] because we investigated absolute rather than relative stereoscopic measurements and because we analyzed horizontally and vertically oriented objects separately. With respect to absolute measurements, Fencil *et al.*[16] imaged a box phantom containing aluminum wires that simulated blood vessels at different angles. Fencil *et al.* employed an automated cross-correlation technique to determine the position of a wire (vessel) segment in the second image of a stereoscopic pair after it was selected in the first image. They obtained an average calculated distance error of approximately ±2 mm, which is similar to our error for vertically oriented fibrils and the errors in the studies of Doi and Duda and Higashida *et al.* that are cited above. Our technique is easier to implement than Fencil *et al.*'s but more observer dependent, as the observer effectively judges the correlation between the cursor and the fibrils in both images of the stereoscopic pair.

The fact that the observers in our study did worse at measuring the depths of horizontally as opposed to vertically oriented fibrils is not surprising since the image discrepancy and hence the stereoscopic effect is less for the horizontal objects (i.e., there is considerable overlap between corresponding horizontally oriented objects in the stereo pairs, and the shifts in positions are not as apparent).[14] There appears to be a larger difference in the performance among the observers for the horizontally oriented fibrils, with one observer performing very well and the other two very poorly. This may be related to different aptitudes for stereoscopic visualization.

The orientations of most objects in actual mammograms are combinations of horizontal and vertical. Further studies are planned to evaluate absolute depth measurements of fibrils oriented at various intermediate angles and of objects of different shapes. The effects of the shape and contrast of the virtual cursor and of the stereo shift angle on the accuracy of the depth measurements will also be investigated. Finally, the cursors will be applied to digital stereomammograms of breast biopsy samples to determine their applicability in estimating lesion depths and dimensions and in providing additional depth cues for improved stereoscopic image interpretation.

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DIGITAL STEREOMAMMOGRAPHY - DEPENDENCE OF DEPTH PERCEPTION ON IMAGING TECHNIQUE

Heang-Ping. Chan, Mitchell. M. Goodsitt, Lubomir. M. Hadjiiski, Chintana. Paramagul and Janet. E. Bailey

Purpose: To compare depth perception in magnification and contact stereomammography by means of an observer study using phantom images of mammographic test objects.

Methods and Materials: Stereo image pairs were acquired with a GE Senographe 2000D digital mammography system using a technique that shifted the object being imaged instead of the focal spot. A modular phantom that contained fibrils embedded on six different layers of Lexan, each layer separated by 2 mm, was designed and built. The fibrils were positioned at random locations within a 5x5 matrix on each layer. A total of 25 fibrils were oriented horizontally and 25 vertically. The fibrils were arranged such that a horizontal and a vertical fibril overlapped as a cross in a projection image. Each image contained 25 crossing fibril pairs in the 5x5 matrix. The layers could be randomly ordered to produce different fibril depth separations at different locations of the matrix. The depth separation of every two crossing fibrils ranged from 2 mm to 10 mm in each phantom configuration. Three phantom configurations were imaged in this study. Stereoscopic pairs of images were acquired using techniques of $\pm 3°$ stereo angle, 30 kVp, Rh/Rh, contact and 1.8X magnification with an exposure range of 4 mAs to 63 mAs. The images were displayed on a Barco monitor driven by a Metheus stereo board and viewed with LCD stereo glasses. Contrast and brightness adjustments and zooming were available on the stereo display workstation. Observers visually judged if the vertical fibril in each pair of crossing fibrils was in front of or behind the horizontal fibril.

Results: In a preliminary study, it was found that the accuracy of depth discrimination increased with increasing fibril depth separation and with increasing x-ray exposure. Zooming the contact stereo images by 2X did not improve the accuracy. Depth discrimination was superior with stereo images acquired using geometric magnification in comparison to those acquired using a contact technique.

Conclusion: Depth discrimination in stereomammography depends on the imaging technique. Magnification stereoscopic imaging may improve the perception of image details and depth separation. This technique may be useful for differentiating overlapping tissues from masses in mammography.

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AbstractID: 7108 Title: The Effect of 2X Zoom on Virtual Cursor Depth Measurements in Stereomammography

We are developing virtual 3-D cursors for measuring depths in digital stereomammograms. Our previous studies showed viewing the images at a 2X-zoom factor did not improve the measurement accuracy. Those studies employed 50-micron pixel images created with a Fischer biopsy unit. We performed a similar study with 100-micron pixel images created with a GE Senographe 2000D digital mammography unit. A phantom containing 25 low contrast fibrils at depths ranging from 1 to 11 mm was imaged. Left and right eye images were generated at stereo shift angles of +/- 2.5° and 5°. The images were displayed in normal and 2X zoom mode. Observers viewed the images with stereo glasses and adjusted the positions of a cross-shaped virtual cursor to best match the perceived location of each fibril. For a trained observer, the standard errors of the estimates (SEEs) of the least-square fits to the measured vs. true depths were 0.59, 0.50, 0.31, and 0.19-mm for the 2.5 °, 2.5 ° zoom, 5 °, and 5 ° zoom images, respectively. The corresponding RMS errors were 0.59, 0.94, 0.39, and 0.40-mm. Use of the 5° stereo angle improved the depth measurement accuracy (RMS error) by 34%. Although zooming the images did not improve depth measurement accuracy, the stereo effect was more readily visualized. This was more apparent than in the 50-micron pixel case. Also, the consistencies of the measurements as determined by the SEEs were improved with zooming. Results for additional observers and for alternative depth calibration methods will be presented.